EVOLUTION OF CLUSTER ELLIPTICALS AT $0.2 < z < 1.2$ FROM HUBBLE SPACE TELESCOPE IMAGING[1,2]

David Schade, L. Felipe Barrientos, & and Omar López-Cruz[3,4]

Department of Astronomy, University of Toronto, 60 St. George St., Toronto, Canada M5S 3H8

ABSTRACT

Two-dimensional surface photometry derived from *Hubble Space Telescope* imaging is presented for a sample of 225 early-type galaxies (assumed to be cluster members) in the fields of 9 clusters at redshifts $0.17 < z < 1.21$. The 94 luminous ellipticals ($M_{AB}(B) < -20$; selected by morphology alone with no reference to color) form tight sequences in the size-luminosity plane. The position of these sequences shifts, on average, with redshift so that an object of a given size at $z = 0.55$ is brighter by $\Delta M(B) = -0.57 \pm 0.13$ mag than its counterpart (measured with the same techniques) in nearby clusters. At $z = 0.9$ the shift is $\Delta M(B) = -0.96 \pm 0.22$ mag. If the relation between size and luminosity is universal so that the local cluster galaxies represent the evolutionary endpoints of those at high redshift, and if the size-luminosity relation is not modified by dynamical processes then this population of galaxies has undergone significant luminosity evolution since $z = 1$ consistent with expectations based on models of passively evolving, old stellar populations.

Subject headings: galaxies:evolution—galaxies:fundamental parameters

[1]Based on observations with the NASA/ESA *Hubble Space Telescope* obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy Inc., under NASA contract NAS 5-26555.

[2]Based on data obtained through the facilities of the Canadian Astronomy Data Centre.

[3]*also* Instituto Nacional de Astrofísica Optica y Electrónica (INAOE), Tonantzintla, México

[4]Visiting Astronomer, Kitt Peak National Observatory, National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

1. INTRODUCTION

Luminosity evolution is an expected consequence of the passive aging of a stellar population such as that believed to make up the bulk of the stars in elliptical galaxies (e.g., Tinsley 1972). Signs of color evolution (which accompanies luminosity evolution) have been reported by Dressler and Gunn (1990), Aragon-Salamanca et al. (1993), Rakos and Schombert (1995), and Oke, Gunn, & Hoessel (1996). These observations are all broadly consistent with theoretical models of old, passively-evolving, elliptical galaxies (e.g., Bruzual & Charlot 1993).

Observations with *Hubble Space Telescope* by Pahre, Djorgovski, & de Carvalho (1996) of a cluster at $z = 0.41$ indicate evolution relative to the local Kormendy (1977) relation of -0.36 ± 0.14 magnitudes in the restframe K-band and Barrientos, Schade, & López-Cruz (1996) find -0.64 ± 0.3 mag of evolution in the size-luminosity relation in that same cluster relative to Coma. Spectroscopic observations by Bender, Ziegler, & Bruzual (1996) and van Dokkum & Franx (1996) result in fundamental plane and Faber-Jackson relations at $z \sim 0.4$ that are both consistent with the photometric evidence for evolution.

Schade et al. (1996a) use two-dimensional modeling techniques to analyze a sample of 166 early-type galaxies and show that cluster and field ellipticals evolve with redshift in the $M_B - \log R_e$ plane (a projection of the fundamental plane). If the $M_B - \log R_e$ relation is not significantly modified by dynamical processes then this is the signature of luminosity evolution of individual galaxies amounting to ~ -0.5 mag at $z = 0.5$. *HST* data yields more precise surface photometry because of its superior resolution. Archival imaging is available for a number of clusters although the *HST* field typically covers less than 1 Mpc^2 so the number of luminous galaxies in a single pointing is small and, furthermore, few redshifts are available. Nevertheless, this approach is complementary to that of Schade et al. (1996a) as a means of detecting the evolution of cluster galaxies.

This *Letter* describes the analysis of two-dimensional surface photometry of a sample of 94 luminous *early-type* galaxies in the fields of 9 clusters at $0.17 < z < 1.21$. Data and procedure are described in §2. The relation between size and luminosity or surface brightness is presented in §3 and the results are discussed in §4. It is assumed throughout this paper that $H_\circ = 50$ km sec^{-1} Mpc^{-1} and $q_\circ = 0.5$.

2. DATA AND PROCEDURE

HST imaging of 9 galaxy clusters with $0.17 < z < 1.21$ was obtained from the *HST* archive using the facilities of the Canadian Astronomy Data Centre. Table 1 gives details of the data. Object catalogs were constructed by eye for all of the clusters and an additional matched-template finding algorithm was applied to those clusters at $z > 0.5$. Elliptical galaxy templates with a variety of sizes, axial ratios, and orientations (90 templates in total) were convolved with the images of the $z > 0.5$ clusters and a detection significance was computed at each pixel of the image. All detections with signal-to-noise ratio greater than 30 were selected and subjected to the fitting procedure. This finding procedure allows the selection limits to be determined so that the limiting surface brightness for detection of an elliptical galaxy of a given size can be computed. Selection lines are shown on Figure 2. The galaxy locus in the $M_B - \log R_e$ plane lies well away from the selection lines except at the highest redshift. Therefore the photometric catalogs are complete in these clusters down to luminosities (and surface brightnesses) well below the sequence of luminous galaxies that is used to derive the shifts in the $M_B - \log R_e$ relation.

Two-dimensional models (exponential disks and $R^{1/4}$ laws) were fitted to the symmetric components of the light distributions of galaxies (see Schade et al. 1995) in order to minimize the effects of nearby companions. Galaxy models were convolved with the empirically-determined point-spread function constructed using the IRAF task DAOPHOT (Stetson 1987). There are typically few bright, unsaturated stars on a WFPC2 frame from which to construct an effective point-spread function (PSF) so a standard WFPC2 PSF constructed from 6 bright stars was adopted for most clusters. The frame-to-frame variations in the PSF (and spatial variations within a frame) contribute about 5% r.m.s. noise to the size measurments when a standard PSF is used. In the few cases where enough stars were available, individual-frame PSFs were constructed.

The idealized galaxy models were convolved with the PSFs and a χ^2 minimization routine was used to find the best-fit model parameters (size, surface brightness, and fractional bulge luminosity, B/T). The error bars shown Figures 1 and 2 are based on output from the fitting routine and are confirmed by simulations to be reasonable in the presence of sky-

subtraction and other random errors. Details of the fitting procedure are given in Schade et al. (1996b). Those objects that were fit well by a single component $R^{1/4}$ law (as judged by this visual inspection of the residuals) were defined as elliptical galaxies for the purposes of the present work. No color information was used in the selection process. A total of more than 1500 objects were fitted and 225 were classified as ellipticals.

The photometric zeropoints from the WFPC2 image headers were used to convert counts to flux densities (Whitmore 1995) and then to AB magnitudes. The AB magnitudes were converted to restframe $M_{AB}(B)$ [$B_{AB} = B - 0.17$] luminosities using interpolation of a *present-day* elliptical galaxy spectral energy distribution (Coleman, Wu, and Weedman 1980) as described by Lilly et al. (1995). The K-correction problem is discussed in §3.

3. RESULTS

An important feature of this study is that the imaging of nearby clusters (obtained with the Kitt Peak 0.9 m telescope [López-Cruz 1996]) which provides the local anchoring point for the $M_B - \log R_e$ relation has similar physical resolution and signal-to-noise ratio to the *HST* data (see Barrientos et al. 1996) and were measured with identical techniques. Thus these B-band measures form a consistent comparison set for the high-redshift galaxies.

Figure 1 shows the relation between $\log R_e$ (half-light radius in kpc) and $M_{AB}(B)$ for elliptical galaxies in 4 nearby clusters. Extinction corrections in the B-band of 0.18 mag for A2256 ($z = 0.0601$), 0.07 mag for A2029 ($z = 0.077$), 0.05 mag for Coma ($z = 0.023$), and 0.04 for A957 ($z = 0.045$) were obtained from the Nasa Extragalactic Database which provides Burstein and Heiles (1982) values with relative errors in $E(B - V)$ estimated at 0.01 mag. With these corrections the $M_B - \log R_e$ relations for these 4 clusters are consistent with one another (the offset in luminosity between A2256 and A2029 which have 38 and 60 elliptical galaxies brighter than $M_{AB}(B) = -20$ is 0.00 ± 0.10 mag) and they were combined to form the adopted local relation: $M_{AB}(B) = -3.33 \log R_e - 18.65 \pm 0.06$. The slope was constrained to agree with Schade et al. (1996a) and the present relation supercedes that work. It fits all of the present data well and the computed offsets between this local relation and those at high redshift is insensitive to this choice.

Figure 2 shows the relation between $\log R_e$ (half-light radius in kpc) and $M_{AB}(B)$ for elliptical galaxies in the fields of 9 clusters at $0.17 < z < 1.21$. Luminosities and sizes are calculated assuming that all galaxies are cluster members. Estimates of contamination by field ellipticals from the counts of Driver et al. (1996) show that contamination of the bright sequence of cluster galaxies ($M_B(AB) < -20$) is less than 1 or 2 galaxies for clusters at $z < 0.55$ although the corrections for higher redshift clusters become significant (e.g., 9 contaminating galaxies in 3C324). However, plots of observed parameters R_e in arcseconds versus apparent magnitude show that the ellipticals in the 3 fields occupy discrete bands. This is a strong indication that the ellipticals are indeed predominantly cluster sequences. [There is a second cluster sequence of 6 galaxies with an estimated redshift of 0.45 in the field of 3C324.] Although some field contamination is likely to be present, it must be smaller than suggested by the counts of Driver et al. (1996) and does not dominate the evolutionary results derived here.

On average, the $M_B - \log R_e$ sequences in Figure 2 shift toward higher luminosity with increasing redshift. The size of the shifts and corresponding errors were computed using the techniques given in Feigelson & Babu (1992) and also computed according to the same procedure used in Schade et al. (1996a). The estimated shifts and errors were virtually identical these two techniques and the results presented here were computed adopting a slope of $\Delta M/\Delta log R_E = -3.33$ to agree with Schade et al. (1996a). Only those galaxies with $M_{AB}(B) < -20$ were included in the computation of ΔM. The two clusters common to the present study and Schade et al. (1996a) have independently measured values of $\Delta M(B)$ (after revisions discussed in §4) that differ by 0.12 ± 0.21 mag [ABELL2390] and 0.03 ± 0.24 mag [CL001558+16].

The adoption of a present-day elliptical spectral energy distribution to compute the restframe B-band (4400 Å) luminosity results in an underestimate (by ~ 0.15 mag at $z = 1$ and less at lower redshift [Charlot, Worthey, & Bressan 1996]) of the B-band luminosity of a younger (bluer) stellar population if the observations are at a restframe wavelength longer than 4400 Å. At z=0.751 and z=0.895 the observed wavelengths are 4576 and 4230$\AA$ respectively in the rest frame so that the uncertainties in the K-corrections are small (< 0.05 mag). The situation is more difficult

at z=1.206 where the observed wavelength (F702W) corresponds to the ultraviolet (3160$\AA$) so that this point is much less secure. Dickinson (1995) suggests that these galaxies, although still very red, are ~ 0.6 mag bluer in $R-K$ than a present-day elliptical. The models of Bruzual & Charlot (1993) predict a change of only ~ 0.4 mag from t=5 Gyr to t=15 Gyr (corresponding roughly to $z = 1$ and the present day). Evolutionary corrections would would decrease the amount of brightening measured at $z = 1.206$.

The effect of cosmology on this result is indicated by the arrows in the lower left of each cluster panel. These show the change in size and luminosity that result from changing $q_\circ = 0.5$ to $q_\circ = 0.1$. The net effect on the computed magnitude shifts is reduced by the fact that much of the change is parallel to the $M_B - \log R_e$ relation. For $q_\circ = 0.1$ stronger evolution would be computed by -0.06 mag at $z = 0.4$, -0.09 mag at $z = 0.55$, and -0.17 mag at $z = 1.2$.

4. DISCUSSION

The relationship between blue luminosity and effective radius for elliptical galaxies in the present sample shifts, on average, with redshift so that at $z = 0.9$ a galaxy of a given size is -0.96 ± 0.22 mag more luminous than its counterpart (of the same size) in our sample of local clusters. If the $M_B - \log R_e$ relation for elliptical galaxies is universal and if dynamical evolution does not modify the $M_B - \log R_e$ relation (e.g., Capelato, de Carvalho, & Carlberg 1995) then this effect is due to luminosity evolution of individual galaxies.

The galaxies in Figure 1 were selected on the basis of their morphology alone with no reference to their color. Only those galaxies that are well-fit by an $R^{1/4}$ law were classified as ellipticals. This selection process was done by visual inspection and is thus subjective although the position of the galaxies on the $M_B - \log R_e$ diagram was not known at the time that the classifications were done. The selection criteria ensure that all of the galaxies included in the present study conform closely to an $R^{1/4}$ law, but some galaxies may have been rejected that would be classified as elliptical galaxies using, e.g., color criteria. The main weakness in the present study is the lack of spectroscopic information so that cluster membership is uncertain. We believe that field galaxy contamination is small (see §3) but these results would clearly be much more secure if these galaxies were confirmed cluster members.

A number of studies detect evolution in the colors of the reddest galaxies in clusters. Aragon-Salamanca et al. (1993), Rakos & Schombert (1995), and Oke, Gunn, & Hoessel (1996) detect color changes that are consistent with old, single-burst models of elliptical galaxies. Spectroscopic studies, although based on small numbers of galaxies, support the conclusions of the photometric work. Bender, Ziegler, & Bruzual (1996) use velocity dispersions and Mg line strengths of 16 galaxies to derive evolution of ~ 0.5 mag in a cluster at $z = 0.37$ and van Dokkum & Franx (1996) detect a few tenths of a magnitude of evolution in the fundamental plane at $z = 0.39$ from observations of 9 galaxies. All of these results imply that the luminosities of ellipticals should be measurably larger at $z > 0.4$.

Figure 3 shows the evolution with redshift of the $M_B - \log R_e$ relation for elliptical galaxies. ΔM is the change in luminosity (or, equivalently, surface brightness) for a galaxy of a given size. Included are results from Schade et al. (1996a) for field and cluster galaxies and from Barrientos et al. (1996). The best-fit relation is $\Delta M = 0.78 \Delta z$. Superimposed upon Figure 3 is the predicted brightening from Buzzoni (1995) for three values of the initial mass function (IMF) and an assumed age of 15 Gyr at the present time. Note that these theoretical tracks are $\Delta M(V)$ rather than B-band values which would be ~ 0.15 mag larger at $z = 1$ (Charlot, Worthey, & Bressan 1996). If the difference in bands is ignored then a best-fit IMF slope is $s = 2.85 \pm 0.2$ (where a Salpeter slope is $s = 2.35$).

It has been shown (Dressler & Gunn 1992) that 13% of the galaxies with deVaucouleurs ($R^{1/4}$) profiles in their set of clusters at $z \sim 0.4$ show spectroscopic evidence of recent star-formation (i.e., have "E+A spectra" showing Balmer absorption). We expect some fraction of our own sample to have E+A spectral energy distributions and such galaxies would contribute to the observed evolution of the $M_B - \log R_e$ relation. If our sample of ellipticals were dominated by such galaxies at high redshift then the observed evolution in the $M_B - \log R_e$ would be strongly affected by recent star-formation.

The improved local calibration of the $M_B - \log R_e$ relation given above results in a downward revision of the amount of evolution found for cluster and field galaxies in Schade et al. (1996a) by 0.02, 0.14, and 0.13 mag for A2390, MS1621+26, and MS0016+16. B-band galactic extinctions are 0.18 mag (A2256),

0.33 mag (A2390), 0.08 (MS1621+26) and 0.11 mag (MS0016+16). All extinctions were obtained from the Nasa Extragalactic Database. The Gunn r extinction is about half of the B-band extinction (Mihalas & Binney 1981). In Schade et al. both the local calibration and the high-redshift cluster photometry were zero-pointed against PPP (Yee 1991) photometry whereas for the present calibration the total galaxy magnitude is obtained from the fitted model parameters (thus the galaxy light is integrated to infinity). The difference amounts to 10-15%.

The evolution found in the present work is consistent with that found by Schade et al. (1996a) to $z = 0.55$ and shows that the evolutionary trend continues to $z \sim 1$. Schade et al. detect no significant difference between field and cluster elliptical galaxy evolution although it is important to note that their cluster sample is dominated by galaxies in regions far from the cluster core. In contrast, the present study is restricted to galaxies less than 1 Mpc from the core. The fact that we see no difference in ΔM_B between these galaxies near the cluster core, those in the outer regions of the cluster, and those in the field, is further evidence for the homogeneous nature of the elliptical galaxy population, (e.g., Bower, Lucey & Ellis 1992). Neither the $M_B - \log R_e$ relation nor its evolution has yet revealed a significant dependence on environment.

We thank Simon Lilly, Ray Carlberg, and Pedro Colin for helpful discussions. We also thank an anonymous referee for suggestions which greatly improved this paper. We thank Eric Feigelson for kindly providing his computer code. The assistance of the Canadian Astronomy Data Centre is very much appreciated. This work was supported financially by NSERC of Canada.

REFERENCES

Aragon-Salamanca,A., Ellis,R., Couch,W., & Carter,D. 1993, MNRAS, 262 764

Barrientos,F., Schade, D., & López-Cruz, O. 1996, ApJ, 460, 89

Bender,R. Ziegler, B., & Bruzual, G. 1996, ApJ, 463, 51

Bower, R., Lucey, J., & Ellis, R. 1992 MNRAS, 254, 601

Bruzual, G. & Charlot 1993, ApJ, 405, 538

Buzzoni, A., 1995, ApJS, 98, 69

Burstein, D. & Heiles, C. 1982, AJ, 887, 1165

Capelato, H., de Carvalho, R., & Carlberg, R. 1995, ApJ, 451, 525 ApJ, 457, 625

Charlot, S., Worthey, G. & Bressan, A. 1996, ApJ, 457, 625

Coleman, G., Wu, C. & Weedman, D. 1980, ApJS, 43, 393

de Carvalho, R., & Djorgovski, S., 1992, ApJ, 389,49

Dickinson, M. 1995 in *Fresh Views of Elliptical Galaxies*, A.S.P. Conference Series, ed. Buzzoni,A., Renzini, A., & Serrano, A. p. 283

van Dokkum, P. & Franx, M. 1996, MNRAS, 281, 985

Dressler, A., & Gunn, J. 1992, ApJS, 78 1

Dressler, A., & Gunn, J. 1990, in *Evolution of the universe of galaxies* , San Francisco,Astronomical Society of the Pacific

Driver, S., Windhorst, R., Phillips, S., & Bristow, P. 1996, ApJ525, 533

Kormendy, J. 1977, ApJ, 218, 333

Feigelson, E., & Babu, G. 1992 ApJ, 397, 55

Lilly, S.J., Tresse, L., Hammer, F., Crampton, D. & Le Fèvre, O. 1995, ApJ, 455, 108

López-Cruz, O. 1996, PhD Thesis, University of Toronto

Mihalas, D., & Binney, J. 1981 in *Galactic Astronomy*, San Francisco, W.H. Freeman and Company, p. 189

Oke, J., Gunn, J., & Hoessel, J. 1996, AJ, 111, 29

Pahre, M., Djorgovski, S., & de Carvalho, R. 1996, ApJ, 456, 79

Rakos,K., & Schombert,J. 1995, ApJ, 439, 47

Schade, D., Carlberg, R., Yee, H., López-Cruz, O., & Ellingson, E. 1996a, ApJ, 464, L63

Schade, D., Lilly, S., Crampton, D., Le Fèvre, O., Hammer, F., & Tresse, L. 1995, ApJ, 451, L1

Schade, D., Lilly, S., Le Fèvre, O., Hammer, F., & Crampton, D. 1996b, ApJ, 464, 79

Stetson, P.B., 1987, PASP, 99, 191

Tinsley, B. 1972, ApJ, 178,319

Whitmore, B. 1995 *Photometry with the WFPC2* available on Space Telescope Science Institute WWW pages.

Yee,H.K.C. 1991, PASP, 103, 396

Yee,H. & Green, R. 1987, ApJ, 319, 28

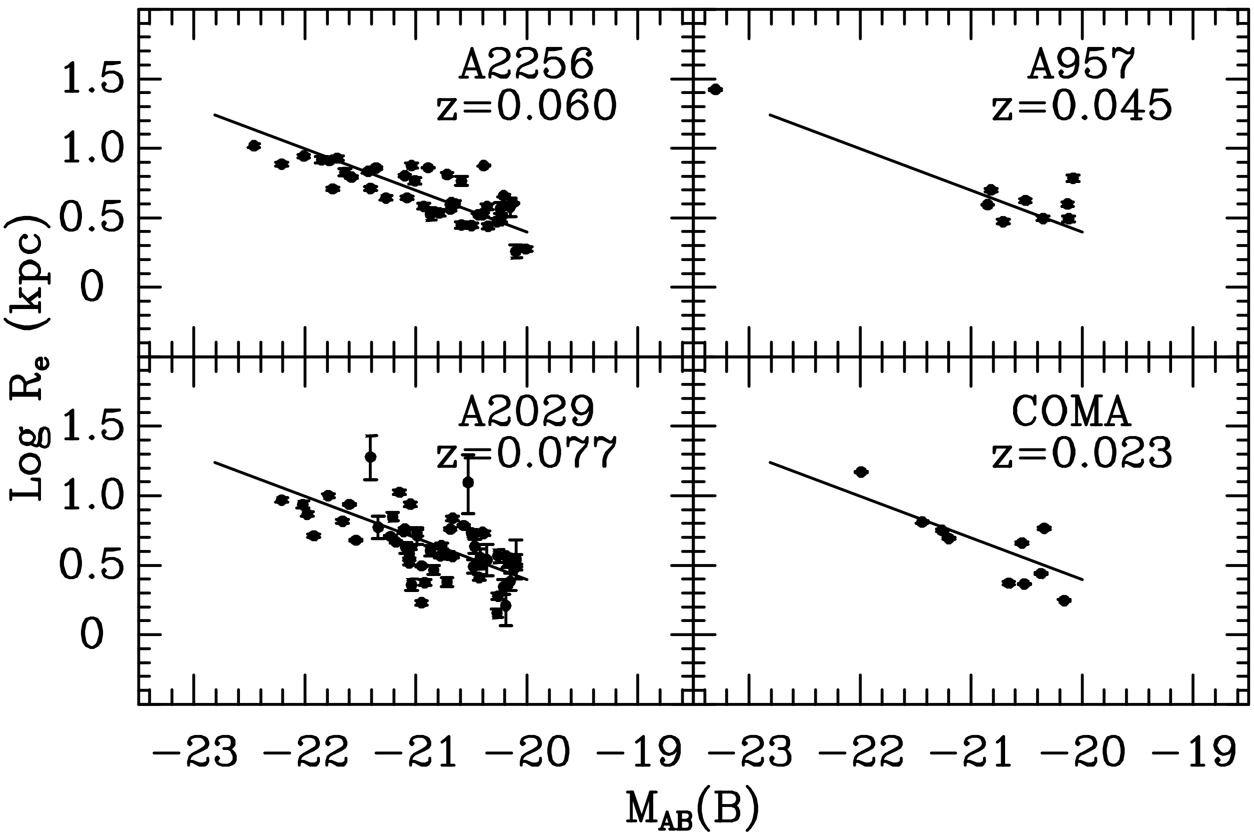
This 2-column preprint was prepared with the AAS LaTeX macros v4.0.

Figure Captions

Fig. 1.— The relations between $M_{AB}(B)$ and $\log R_e$ (half-light radius in kpc) for elliptical galaxies in nearby clusters. These four clusters together form the adopted local relation against which the high-redshift results are compared.

Fig. 2.— The relation between $M_{AB}(B)$ and $\log R_e$ for elliptical galaxies in moderate and high-redshift clusters. The solid line in all panels corresponds to the best-fit to the local sequence (upper left panel) defined in Figure 1 and the dashed lines indicate the best-fit fixed-slope ($\Delta M_B/\Delta \log R_e = -3.33$) relation for each cluster. The fits were restricted to those galaxies with $M_{AB}(B) < -20$ in all clusters. Arrows indicate the effect of changing $q_\circ = 0.5$ to $q_\circ = 0.1$. For those clusters at $z > 0.5$ we also show the selection line (signal-to-noise ratio greater than 30 from the matched-template finding algorithm described in the text) as a dashed line in the upper-right corner of those panels. Elliptical galaxies to the left of that line will be detected.

Fig. 3.— The luminosity shift ΔM_B including revised results from Schade et al. (1996a) and from Barrientos et al. (1996). Filled symbols are for clusters in the present study, open circles are cluster points from Schade et al. (1996a) (including 2 clusters in common that have been offset in redshift slightly for clarity) and open squares are field galaxies from Schade et al. (1996a). The lines are from the models of Buzzoni (1995) for IMF power-law indices of $s = 3.35$ (solid line), $s = 2.35$ (short dashed), and $s = 1.35$ (long dashed). The models assume a present-day age of 15 Gyr and we show the theoretical $\Delta M(V)$ whereas the data is in M_B where the evolution would be ~ 0.15 mag larger by $z = 1$.



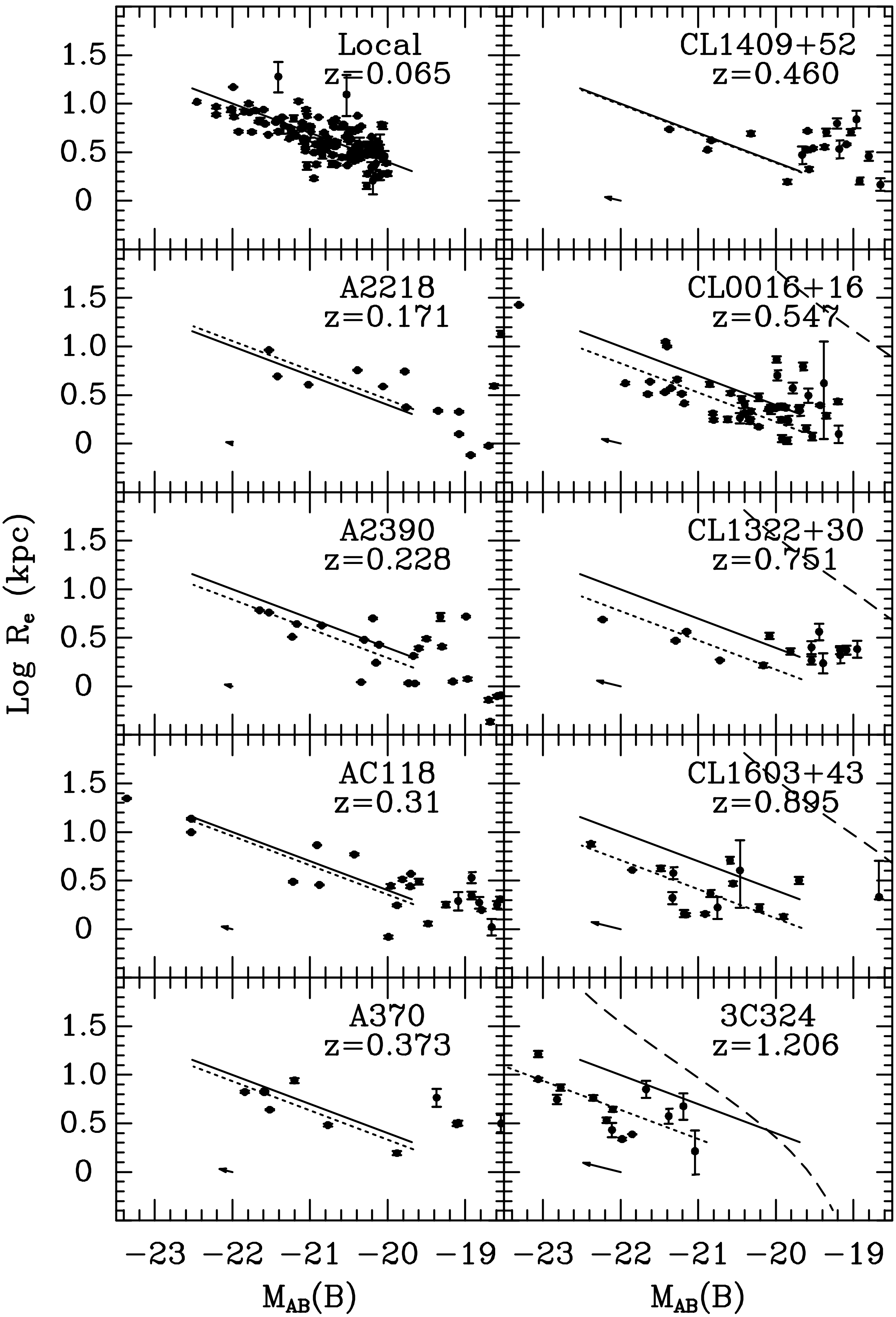
A2256
z=0.060
A957
z=0.045
A2029
z=0.077
COMA
z=0.023
Log R_e (kpc)
$M_{AB}(B)$

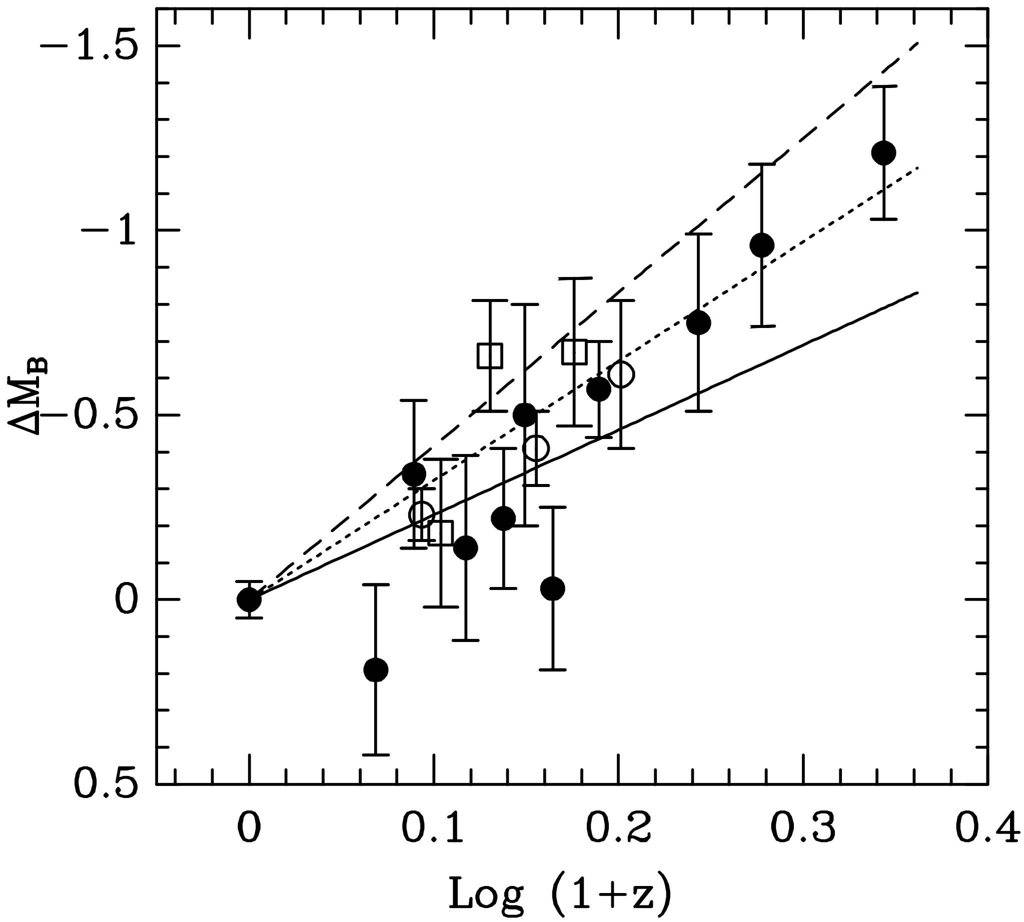
TABLE 1

Evolution of the $M_B - \log R_e$ relation for HST clusters

Cluster	z	ΔM_B	N	Filter	λ(rest) Å	Time (sec)	A_B
A2218	0.171	$+0.19 \pm 0.23$	5	F702W	5960	6500	0.08
ABELL2390	0.228	-0.34 ± 0.20	10	F814W	6530	10500	0.32
AC118	0.310	-0.14 ± 0.25	7	F702W	5330	6500	0.52
ABELL370	0.373	-0.22 ± 0.19	6	F814W	5840	10500	0.07
CL140933+52	0.46	-0.03 ± 0.22	4	F702W	4780	12600	0.00
CL001558+16	0.547	-0.57 ± 0.13	28	F814W	5180	16800	0.11
CL1322+3027	0.751	-0.75 ± 0.24	6	F814W	4576	32000	0.00
CL1603+4313	0.895	-0.96 ± 0.22	14	F814W	4230	32000	0.01
3C324	1.206	-1.21 ± 0.18	14	F702W	3160	64800	0.13

Note.—N gives the number of galaxies with $M_B(AB) < -20$ that were used to derive the values of ΔM_B given in this table. These results assume $q_\circ = 0.5$ and the effect of cosmology appears in the text. The names are as given in the TARGNAME parameter of the HST observations (sometimes with leading characters,e.g., "GAL-CLUS" stripped off). Note that CL001558+16 is MS0016+16 of Schade et al. (1996a). A_B is the B-band extinction obtained from the NASA Extragalactic Database.


Local
z=0.065
CL1409+52
z=0.460
A2218
z=0.171
CL0016+16
z=0.547
A2390
z=0.228
CL1322+30
z=0.751
AC118
z=0.31
CL1603+43
z=0.895
A370
z=0.373
3C324
z=1.206
Log R_e (kpc)
$M_{AB}(B)$
$M_{AB}(B)$
1.5
1.0
0.5
0
−23
−22
−21
−20
−19



−1.5
−1
−0.5
0
0.5
ΔM_B
0
0.1
0.2
0.3
0.4
Log (1+z)